GLUON RADIATION PATTERNS IN HARD SCATTERING EVENTS[*]

D. Zeppenfeld

Department of Physics, University of Wisconsin, 1150 University Ave.
Madison, WI 53706, USA
E-mail: dieter@phenom.physics.wisc.edu

ABSTRACT

The radiation pattern of relatively soft gluons in hard scattering events is sensitive to the underlying color structure. As an example I consider heavy Higgs production via weak boson fusion at the LHC. A minijet veto, which makes use of the different patterns for signal and backgrounds, provides an effective Higgs search tool.

Finding ways to detect a heavy Higgs boson or longitudinal weak boson scattering at the LHC is an issue of highest importance as long as the nature of spontaneous electroweak symmetry breaking remains to be established. In order to distinguish weak boson scattering, *i.e.* the electroweak process $qq \rightarrow qqVV$, from large backgrounds due to QCD processes and/or the production of W bosons from the decay of top quarks, tagging of at least one fast forward jet is essential.[1] Early studies[2] showed that double tagging is quite costly to the signal rate because one of the two quark jets has substantially lower median p_T (order 30 GeV) than the other (order 80 GeV). Single forward jet tagging relies only on the higher p_T tag-jet and thus proves an effective technique.[3,4]

A study of the WW signal must exploit additional identifying characteristics. For example, the W bosons from top quark decays can be rejected by vetoing the additional central b quark jets arising in $t \rightarrow Wb$.[3] For $H \rightarrow W^+W^- \rightarrow \ell^+\nu\ell^-\bar{\nu}$ another important discriminator is a large transverse momentum difference between the charged leptons.[4]

In a weak boson scattering event no color is exchanged between the initial state quarks. Color coherence between initial and final state gluon bremsstrahlung then leads to a suppression of hadron production in the central region, between the two tagging jet candidates of the signal.[5,6] Typical backgrounds like $t\bar{t}$ production or QCD jet emission in W^+W^- production involve color exchange between the incident partons and, as a result, gluon radiation into the central region dominates.

A second distinction is the momentum scale of the hard process which governs additional gluon radiation. In longitudinal weak boson scattering the color charges, carried by the incident quarks, receive a momentum transfer of order the transverse momentum of the final state quarks which typically is in the $Q = 30$ to 80 GeV range. For the background processes, on the other hand, the color charges receive a much

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larger momentum kick, of the order of the weak boson pair mass or even the parton center of mass energy of the event, *i.e.* $Q \approx 1$ TeV. Extra parton emission is suppressed by a factor $f_s = \alpha_s \ln (Q^2/p_{T,\min}^2)$, where $p_{T,\min}$ is the minimal transverse momentum required for a parton to qualify as a jet. The jet transverse momentum scale below which multiple minijet emission must be expected is set by $f_s = 1$. Because the hard scale Q is much larger for the backgrounds than for the signal a veto on additional minijet activity should provide an efficient tool to suppress the backgrounds, with little cost to the signal. In effect such a technique constitutes a rapidity gap trigger at the minijet level instead of the soft hadron level as was suggested previously.[5] At the LHC the low signal cross sections require running at high luminosity and then overlapping events in a single bunch crossing will likely fill a rapidity gap with soft hadrons even if it is present at the level of a single pp collision. However, even at $\mathcal{L} = 10^{34}$cm^{-2}sec^{-1} only about 20% of random bunch crossings are expected to lead to a jet with $p_T > 20$ GeV[7] and hence a rapidity gap of minijets may well be observable at design luminosity.

In a recent paper[8] these ideas were analyzed in detail for a particular example of longitudinal weak boson scattering: production and subsequent decay $H \to W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$ of a heavy Higgs boson. I would like to summarize the results in the remainder of this talk. At the same time it should be stressed that the basic method is more general: it can be applied to the study of longitudinal weak boson scattering in all channels.

The analysis of Ref. 8 is based on full tree level simulations of the partonic subprocesses for the signal and the backgrounds. The backgrounds considered are $q\bar{q} \to W^+W^-$ with additional QCD radiation of up to two partons, $pp \to t\bar{t}$+n jets, n = $0, 1, 2$ with subsequent top quark decays $t\bar{t} \to bW^+\bar{b}W^-$, and the electroweak background from transversely polarized W's in weak boson scattering subprocesses like $qq \to qq(g)W^+W^-$. This electroweak background is taken as the SM cross section without a heavy Higgs boson and thus the signal is defined as $\sigma(m_H) - \sigma(m_H = 100 \text{ GeV})$. In all cases the leptonic decays of the W's are implemented in the narrow width approximation, at the amplitude level.

In order to identify the signal we first consider events with two well isolated, central leptons ($\ell = e, \mu$):

$$p_{T\ell} > 50 \text{ GeV} , \qquad |\eta_\ell| < 2 \quad , \qquad R_{\ell j} = \sqrt{(\eta_\ell - \eta_j)^2 + (\phi_\ell - \phi_j)^2} > 0.7 ,$$
$$\Delta p_{T\ell\ell} = |\mathbf{p}_{T\ell_1} - \mathbf{p}_{T\ell_2}| \quad > \quad 300 \text{ GeV} , \qquad m_{\ell\ell} > 200 \, GeV . \tag{1}$$

The $R_{\ell j} > 0.7$ separation cut forbids a parton (jet) of $p_T > 20$ GeV in a cone of radius 0.7 around the lepton direction. The cut on $\Delta p_{T\ell\ell}$, the difference of the charged lepton transverse momentum vectors,[4] is crucial to concentrate on high invariant mass and high p_T W pairs. The cross sections after these lepton cuts are given in the first column of the table.

Next we require the existence of a tagging jet, which is taken as the highest transverse momentum parton, which must then satisfy

$$p_{Tj}^{\text{tag}} > 50 \text{ GeV} , \qquad E_j^{\text{tag}} > 500 \text{ GeV} , \qquad 1.5 < |\eta_j^{\text{tag}}| < 4.5 . \tag{2}$$

Table 1. Signal and background cross sections $B\sigma$ in fb after increasingly stringent cuts. Four leptonic decay channels of the W^+W^- pair are included.

	lepton cuts only	+ tagging jet	+ lepton-tagging jet separation	+ minijet veto $(p_{T,\text{veto}} = 20\ \text{GeV})$
	[Eq. (1)]	[Eq. (2)]	[Eq. (3)]	[Eq. (4)]
$WW(jj)$	27.4	1.73	0.57	0.13
$t\bar{t}(jj)$	640	57	25	0.47
$m_H = 100$ GeV	1.18	0.56	0.29	0.18
$m_H = 800$ GeV	3.4	1.79	1.31	0.97
signal	2.2	1.23	1.02	0.79

In addition the tagging jet must be well separated from the W decay leptons,

$$\min |\eta_j^{\text{tag}} - \eta_\ell| > 1.7 \,, \tag{3}$$

The signal and background cross sections after the cuts of Eqs. 2 and 3 are listed in the second and third columns of the table, respectively.
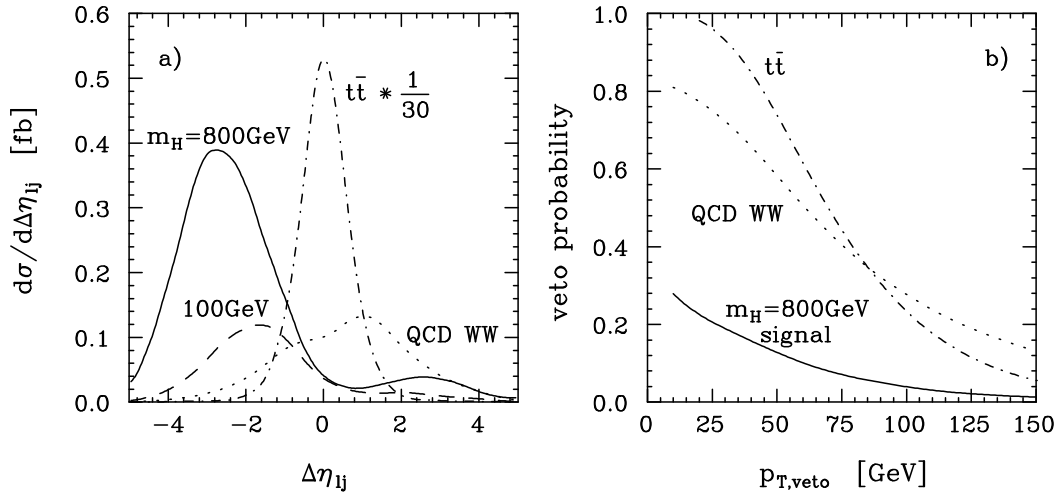

Fig. 1: Rapidity and transverse momentum distributions of secondary jets. In a) $\Delta\eta_{\ell j}$ measures the pseudorapidity distance of the jet closest to the leptons from the average lepton rapidity $\bar{\eta}$. Negative values of $\Delta\eta_{\ell j}$ correspond to soft jets on the opposite side of the leptons with respect to the tagging jet. The dashed line shows the distribution for the electroweak background as defined by the $m_H = 100$ GeV case. The $t\bar{t}jj$ background has been scaled down by a factor $1/30$. The probability to find a veto jet candidate above a transverse momentum $p_{T,\text{veto}}$ in the veto region of Eq. (4) is shown in b).

The cuts discussed so far define the hard scattering event. What are the features of the soft radiation patterns in these events? Fig. 1a shows the angular distribution of

the jet (parton with $p_T > 20$ GeV) closest to the leptons (more precisely, closest to the average lepton rapidity $\bar{\eta} = (\eta_{\ell^+} + \eta_{\ell^-})/2$). The background processes favor emission close to the leptons while the closest jet in the Higgs signal is typically the second quark in the $qq \to qqH$ process. Vetoing any jets in the veto region defined by

$$p_{Tj}^{\text{veto}} > p_{T,\text{veto}} , \qquad \eta_j^{\text{veto}} \varepsilon \; [\eta_\ell^{\min} - 1.7, \eta_j^{\text{tag}}] \;\; \text{or} \;\; [\eta_j^{\text{tag}}, \eta_\ell^{\max} + 1.7] , \qquad (4)$$

will thus substantially reduce the backgrounds while having little effect on the Higgs signal. The veto probability as a function of the cut value $p_{T,\text{veto}}$ is shown in Fig. 1b. Even though these results were obtained in the truncated shower approximation and a more precise modeling is needed, they clearly demonstrate that, in the central region, the backgrounds have a much higher probability to produce additional minijets from QCD radiation. Even in the $t\bar{t}$ background, where a strong suppression is obtained by vetoing the central b-quark jets arising from the top decays, the veto on the jet activity from soft QCD radiation provides an additional background suppression by a factor 2 for $p_{T,\text{veto}} = 20$ GeV. Final cross section values for signal and backgrounds are given in the last column of the Table.

Should minijet vetoing be possible at the LHC for even smaller $p_{T,\text{veto}}$ values the $t\bar{t}$ background to $H \to WW$ events can effectively be eliminated. If low transverse momentum jets ($p_T \approx 30$ GeV) can also be identified in the forward region, then double forward jet-tagging will provide an additional strong suppression of the top quark background.

Acknowledgements

References

1. R. N. Cahn *et al.*, Phys. Rev. **D35**, 1626 (1987); V. Barger *et al.*, Phys. Rev. **D37** 2005 (1988); R. Kleiss and W. J. Stirling, Phys. Lett. **200B**, 193 (1988).
2. U. Baur and E. W. N. Glover, Nucl. Phys. **B347**, 12 (1990); D. Froideveaux, in *Proceedings of the ECFA Large Hadron Collider Workshop*, Aachen, Germany, 1990, edited by G. Jarlskog and D. Rein (CERN report 90-10, Geneva, Switzerland, 1990), Vol II, p. 444; M. H. Seymour, *ibid*, p. 557.
3. V. Barger *et al.*, Phys. Rev. **D44**, 2701 (1991); **48** 5444E (1993); **48**, 5433 (1993).
4. D. Dicus *et al.*, Phys. Lett. **B258**, 475 (1991); Nucl. Phys. **B377**, 31 (1991).
5. Y. L. Dokshitzer, V. A. Khoze, and S. Troyan, in *Proceedings of the 6th International Conference on Physics in Collisions*, (1986) ed. M. Derrick (World Scientific, Singapore, 1987) p.365; J. D. Bjorken, Int. J. Mod. Phys. **A7**, 4189 (1992); Phys. Rev. **D47**, 101 (1993); preprint SLAC-PUB-5823 (1992).
6. J. F. Gunion *et al.*, *Phys. Rev.* **D40** (1989) 2223.

7. G. Ciapetta and A. DiCiaccio, in *Proceedings of the ECFA Large Hadron Collider Workshop*, Aachen, Germany, 1990, edited by G. Jarlskog and D. Rein (CERN report 90-10, Geneva, Switzerland, 1990), Vol II, p. 155.
8. V. Barger, R. J. N. Phillips, and D. Zeppenfeld, Phys. Lett. **B346**, 106 (1995).